

SOME ISSUES RELATED TO THE DIRECT DETECTION OF SUSY DARK MATTER.

J.D. VERGADOS^{A,B}

^A*Theoretical Physics Division, University of Ioannina, Gr 451 10, Ioannina, Greece.*

^B*T-DO, Theoretical Physics Division, LANL, Los Alamos, N.M. 87545.*

Since the expected rates for neutralino-nucleus scattering are expected to be small, one should exploit all the characteristic signatures of this reaction. Such are: (i) In the standard recoil measurements the modulation of the event rate due to the Earth's motion. (ii) In directional recoil experiments the correlation of the event rate with the sun's motion. One now has both modulation, which is much larger and depends not only on time, but on the direction of observation as well, and a large forward-backward asymmetry. (iii) In non recoil experiments gamma rays following the decay of excited states populated during the Nucleus-LSP collision. Branching ratios of about 6 percent are possible.

1. Introduction

It is now established that dark matter constitutes about 30 % of the energy matter in the universe. The evidence comes from the cosmological observations ¹, which when combined lead to:

$$\Omega_b = 0.05, \Omega_{CDM} = 0.30, \Omega_\Lambda = 0.65$$

and the rotational curves ². It is only the direct detection of dark matter, which will unravel the nature of the constituents of dark matter. In fact one such experiment, the DAMA, has claimed the observation of such signals, which with better statistics has subsequently been interpreted as modulation signals ³. These data, however, if they are due to the coherent process, are not consistent with other recent experiments, see e.g. EDELWEISS and CDMS ⁴.

Supersymmetry naturally provides candidates for the dark matter constituents. In the most favored scenario of supersymmetry the LSP can be simply described as a Majorana fermion (LSP or neutralino), a linear combination of the neutral components of the gauginos and higgsinos ⁵⁻⁸. We are not going to address issues related to SUSY in this paper, since

thy have already been addressed by other contributors to these proceeding. Most models predict nucleon cross sections much smaller the the present experimental limit $\sigma_S \leq 10^{-5} pb$ for the coherent process. As we shall see below the constraint on the spin cross-sections is less stringent.

Since the neutralino is expected to be non relativistic with average kinetic energy $\langle T \rangle \approx 40 KeV (m_\chi/100 GeV)$, it can be directly detected mainly via the recoiling of a nucleus (A,Z) in elastic scattering. In some rare instances the low lying excited states may also be populated⁹. In this case one may observe the emitted γ rays.

In every case to extract from the data information about SUSY from the relevant nucleon cross section, one must know the relevant nuclear matrix elements¹⁰⁻¹¹. The static spin matrix elements used in the present work can be found in the literature⁹.

Anyway since the obtained rates are very low, one would like to be able to exploit the modulation of the event rates due to the earth's revolution around the sun^{12,13}. In order to accomplish this one adopts a folding procedure, i.e one has to assume some velocity distribution^{12,13,14,15} for the LSP. One also would like to exploit other signatures expected to show up in directional experiments¹⁶. This is possible, since the sun is moving with relatively high velocity with respect to the center of the galaxy.

2. Rates

The differential non directional rate can be written as

$$dR_{undir} = \frac{\rho(0)}{m_\chi} \frac{m}{Am_N} d\sigma(u, v) |v| \quad (1)$$

where $d\sigma(u, v)$ was given above, $\rho(0) = 0.3 GeV/cm^3$ is the LSP density in our vicinity, m is the detector mass and m_χ is the LSP mass

The directional differential rate, in the direction \hat{e} of the recoiling nucleus, is:

$$dR_{dir} = \frac{\rho(0)}{m_\chi} \frac{m}{Am_N} |v| \hat{v} \cdot \hat{e} \Theta(\hat{v} \cdot \hat{e}) \frac{1}{2\pi} d\sigma(u, v) \delta\left(\frac{\sqrt{u}}{\mu_r v \sqrt{2}} - \hat{v} \cdot \hat{e}\right)$$

where $\Theta(x)$ is the Heaviside function and:

$$d\sigma(u, v) = \frac{du}{2(\mu_r bv)^2} [(\bar{\Sigma}_S F(u)^2 + \bar{\Sigma}_{spin} F_{11}(u))] \quad (2)$$

where u the energy transfer Q in dimensionless units given by

$$u = \frac{Q}{Q_0} \quad , \quad Q_0 = [m_p Ab]^{-2} = 40 A^{-4/3} MeV \quad (3)$$

with b is the nuclear (harmonic oscillator) size parameter. $F(u)$ is the nuclear form factor and $F_{11}(u)$ is the spin response function associated with the isovector channel.

The scalar cross section is given by:

$$\bar{\Sigma}_S = \left(\frac{\mu_r}{\mu_r(p)}\right)^2 \sigma_{p,\chi^0}^S A^2 \left[\frac{1 + \frac{f_S^1}{f_S^0} \frac{2Z-A}{A}}{1 + \frac{f_S^1}{f_S^0}} \right]^2 \approx \sigma_{N,\chi^0}^S \left(\frac{\mu_r}{\mu_r(p)}\right)^2 A^2 \quad (4)$$

(since the heavy quarks dominate the isovector contribution is negligible). σ_{N,χ^0}^S is the LSP-nucleon scalar cross section. The spin Cross section is given by:

$$\bar{\Sigma}_{spin} = \left(\frac{\mu_r}{\mu_r(p)}\right)^2 \sigma_{p,\chi^0}^{spin} \zeta_{spin}, \zeta_{spin} = \frac{1}{3(1 + \frac{f_A^0}{f_A^1})^2} S(u) \quad (5)$$

$$S(u) \approx S(0) = \left[\left(\frac{f_A^0}{f_A^1} \Omega_0(0)\right)^2 + 2 \frac{f_A^0}{f_A^1} \Omega_0(0) \Omega_1(0) + \Omega_1(0)^2 \right] \quad (6)$$

f_A^0, f_A^1 are the isoscalar and the isovector axial current couplings at the nucleon level obtained from the corresponding ones given by the SUSY models at the quark level, $f_A^0(q), f_A^1(q)$, via renormalization coefficients g_A^0, g_A^1 , i.e. $f_A^0 = g_A^0 f_A^0(q), f_A^1 = g_A^1 f_A^1(q)$. These couplings and the associated nuclear matrix elements are normalized so that, for the proton at $u = 0$, yield $\zeta_{spin} = 1$. If the nuclear contribution comes predominantly from protons ($\Omega_1 = \Omega_0 = \Omega_p$), $S(u) \approx \Omega_p^2$ and one can extract from the data the proton cross section. If the nuclear contribution comes predominantly from neutrons ($\Omega_0 = -\Omega_1 = \Omega_n$) one can extract the neutron cross section. In many cases, however, one can have contributions from both protons and neutrons. The situation is then complicated, but it turns out that $g_A^0 = 0.1$, $g_A^1 = 1.2$. Thus the isoscalar amplitude is suppressed, i.e. $S(0) \approx \Omega_1^2$. Then the proton and the neutron spin cross sections are the same.

3. Results

To obtain the total rates one must fold with LSP velocity and integrate the above expressions over the energy transfer from Q_{min} determined by the detector energy cutoff to Q_{max} determined by the maximum LSP velocity (escape velocity, put in by hand in the Maxwellian distribution), i.e. $v_{esc} = 2.84 v_0$ with v_0 the velocity of the sun around the center of the galaxy (229 Km/s).

3.1. Non directional rates

Ignoring the motion of the Earth the total non directional rate is given by

$$R = \bar{K} \left[c_{coh}(A, \mu_r(A)) \sigma_{p, \chi^0}^S + c_{spin}(A, \mu_r(A)) \sigma_{p, \chi^0}^{spin} \zeta_{spin} \right] \quad (7)$$

where $\bar{K} = \frac{\rho(0)}{m_{\chi^0}} \frac{m}{m_p} \sqrt{\langle v^2 \rangle}$ and

$$c_{coh}(A, \mu_r(A)) = \left[\frac{\mu_r(A)}{\mu_r(p)} \right]^2 A t_{coh}(A), \quad c_{spin}(A, \mu_r(A)) = \left[\frac{\mu_r(A)}{\mu_r(p)} \right]^2 \frac{t_{spin}(A)}{A} \quad (8)$$

where t is the modification of the total rate due to the folding and nuclear structure effects. It depends on Q_{min} , i.e. the energy transfer cutoff imposed by the detector and $a = [\mu_r b v_0 \sqrt{2}]^{-1}$. The parameters $c_{coh}(A, \mu_r(A))$, $c_{spin}(A, \mu_r(A))$, which give the relative merit for the coherent and the spin contributions in the case of a nuclear target compared to those of the proton, are tabulated in table 1 for energy cutoff $Q_{min} = 0, 10$ keV. Via Eq. (7) we can extract the nucleon cross section from the data.

Using $\Omega_1^2 = 1.22$ and $\Omega_1^2 = 2.8$ for ^{127}I and ^{19}F respectively the extracted nucleon cross sections satisfy:

$$\frac{\sigma_{p, \chi^0}^{spin}}{\sigma_{p, \chi^0}^S} = \left[\frac{c_{coh}(A, \mu_r(A))}{c_{spin}(A, \mu_r(A))} \right] \frac{3}{\Omega_1^2} \Rightarrow \approx \times 10^4 \quad (A = 127), \quad \approx \times 10^2 \quad (A = 19) \quad (9)$$

It is for this reason that the limit on the spin proton cross section extracted from both targets is much poorer. For heavy LSP, ≥ 100 GeV, due to the nuclear form factor, $t_{spin}(127) < t_{spin}(19)$. This disadvantage cannot be overcome by the larger reduced mass (see Fig. 1). It even becomes worse, if the effect of the spin ME is included. For the coherent process, however, the light nucleus is no match (see Table 1 and Fig. 2).

3.2. Modulated Rates.

If the effects of the motion of the Earth around the sun are included, the total non directional rate is given by

$$R = \bar{K} \left[c_{coh}(A, \mu_r(A)) \sigma_{p, \chi^0}^S (1 + h(a, Q_{min}) \cos \alpha) \right] \quad (10)$$

and an analogous one for the spin contribution. h is the modulation amplitude and α is the phase of the Earth, which is zero around June 2nd. The modulation amplitude would be an excellent signal in discriminating against background, but unfortunately it is very small, less than two per

Table 1. The factors $c19 = c_{coh}(19, \mu_r(19))$, $s19 = c_{spin}(19, \mu_r(19))$ and $c127 = c_{coh}(127, \mu_r(127))$, $s127 = c_{spin}(127, \mu_r(127))$ for two values of $Q = Q_{min}$.

| Q | | m_χ (GeV) | | | | | | | |
|-----|------|----------------|-------|-------|--------|--------|--------|--------|--------|
| keV | | 20 | 30 | 40 | 50 | 60 | 80 | 100 | 200 |
| 0 | c19 | 2080 | 2943 | 3589 | 4083 | 4471 | 5037 | 5428 | 6360 |
| 0 | s19 | 5.7 | 8.0 | 9.7 | 10.9 | 11.9 | 13.4 | 14.4 | 16.7 |
| 0 | c127 | 37294 | 63142 | 84764 | 101539 | 114295 | 131580 | 142290 | 162945 |
| 0 | s127 | 2.2 | 3.7 | 4.9 | 5.8 | 6.5 | 7.6 | 8.4 | 10.4 |
| 10 | c19 | 636 | 1314 | 1865 | 2302 | 2639 | 3181 | 3487 | 4419 |
| 10 | s19 | 1.7 | 3.5 | 4.9 | 6.0 | 6.9 | 8.3 | 9.1 | 11.4 |
| 10 | c127 | 0 | 11660 | 24080 | 36243 | 45648 | 58534 | 69545 | 83823 |
| 10 | s127 | 0 | 0.6 | 1.3 | 1.9 | 2.5 | 3.3 | 4.0 | 5.8 |

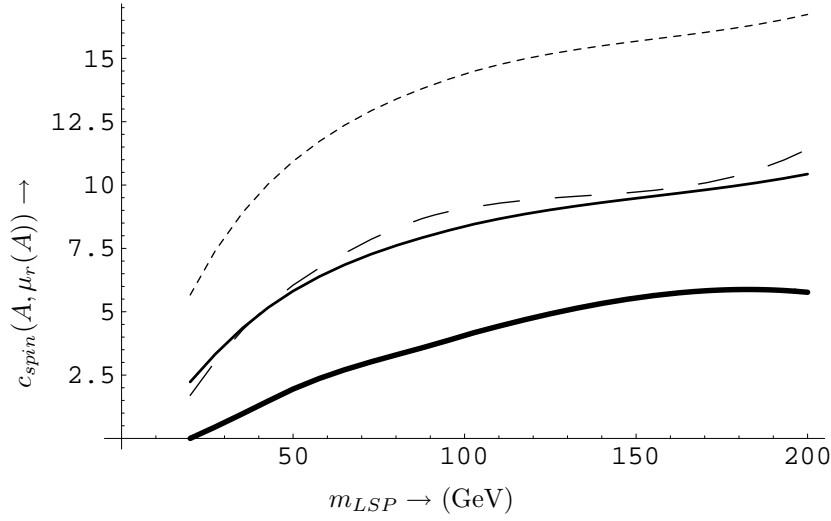
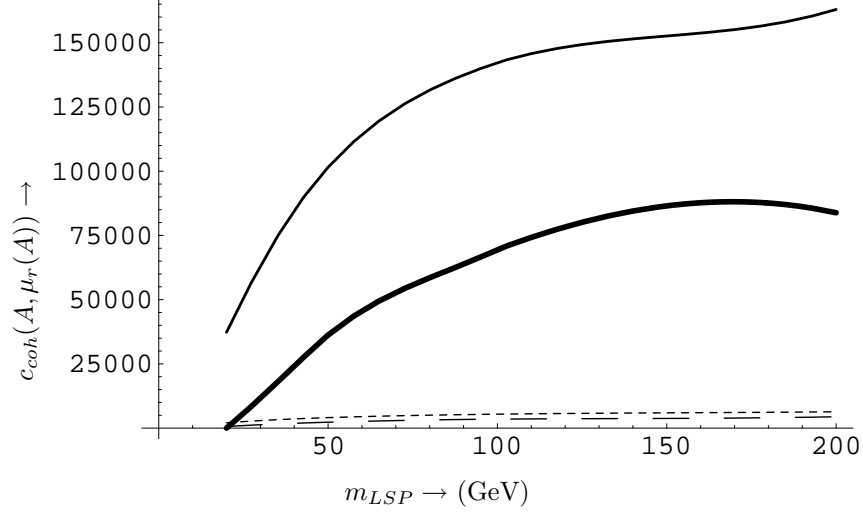
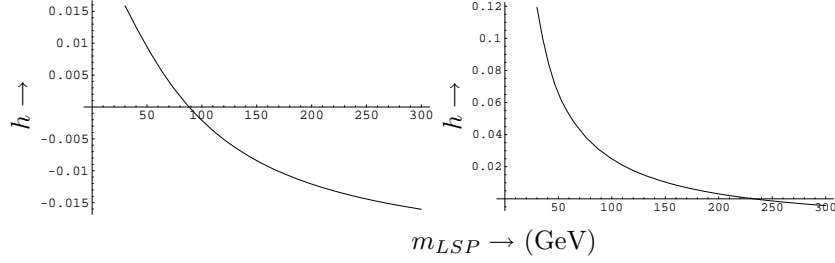


Figure 1. The coefficient $c_{spin}(A, \mu_r(A))$ as a function of the LSP mass. The dashed curves correspond to the ^{19}F system (the short for $Q_{min} = 0$, and the long for $Q_{min} = 10$ keV). The solid curves correspond to the ^{127}I (the thin for $Q_{min} = 0$ and the thick for $Q_{min} = 10$ keV).

cent. Furthermore for intermediate and heavy nuclei, it can even change sign for sufficiently heavy LSP (see Fig. 3). So in our opinion a better signature is provided by directional experiments, which measure the direction of the recoiling nucleus.

Figure 2. The same as in Fig. 1 for the coefficient $c_{coh}(A, \mu_r(A))$.Figure 3. The modulation amplitude h as a function of the LSP mass in the case of ^{127}I for $Q_{min} = 0$ on the left and $Q_{min} = 10$ keV on the right.

3.3. Directional Rates.

Since the sun is moving around the galaxy in a directional experiment, i.e. one in which the direction of the recoiling nucleus is observed, one expects a strong correlation of the event rate with the motion of the sun. In fact the directional rate can be written as:

$$R_{dir} = \frac{\kappa}{2\pi} \bar{K} [c_{coh}(A, \mu_r(A)) \sigma_{p,\chi^0}^S (1 + h_m \cos(\alpha - \alpha_m \pi))] \quad (11)$$

and an analogous one for the spin contribution. The modulation now is h_m , with a shift $\alpha_m \pi$ in the phase of the Earth α , depending on the direction of

Table 2. The parameters t , h , κ , h_m and α_m for $Q_{min} = 0$. The results shown are for the light systems. $+x$ is radially out of the galaxy, $+z$ is in the sun's motion and $+y$ vertical to the plane of the galaxy so that $((x, y, z))$ is right-handed. $\alpha_m = 0, 1/2, 1, 3/2$ implies that the maximum occurs on June, September, December and March 2nd respectively.

| type | t | h | dir | κ | h_m | α_m |
|------|------|------|-------|----------|-------|------------|
| dir | | | +z | 0.0068 | 0.227 | 1 |
| | | | +(-)x | 0.080 | 0.272 | 3/2(1/2) |
| | | | +(-)y | 0.080 | 0.210 | 0 (1) |
| | | | -z | 0.395 | 0.060 | 0 |
| all | 1.00 | | | | | |
| all | | 0.02 | | | | |

observation. $\kappa/(2\pi)$ is the reduction factor of the unmodulated directional rate relative to the non-directional one. The parameters κ , h_m , α_m strongly depend on the direction of observation. We prefer to use the

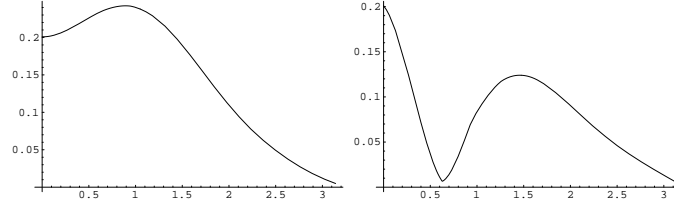


Figure 4. The expected modulation amplitude h_m for $A = 127$ in a direction outward from the galaxy on the left and perpendicular to the galaxy on the right as a function of the polar angle measured from the sun's velocity. For angles than $\pi/2$ it is irrelevant since the event rates are tiny.

parameters κ and h_m , since, being ratios, are expected to be less dependent on the parameters of the theory. In the case of $A = 127$ we exhibit the the angular dependence of h_m for an LSP mass of $m_\chi = 100\text{GeV}$ in Fig. 4. We also exhibit the parameters t , h , κ , h_m and α_m for the target $A = 19$ in Table 2 (for the other light systems the results are almost identical). The asymmetry in the direction of the sun's motion¹⁷ is quite large, ≈ 0.97 , while in the perpendicular plane the asymmetry equals the modulation. For a heavier nucleus the situation is a bit complicated. Now the parameters κ and h_m depend on the LSP mass as well. (see Figs 5 and 6). The asymmetry and the shift in the phase of the Earth are similar to those of

the $A = 19$ system.

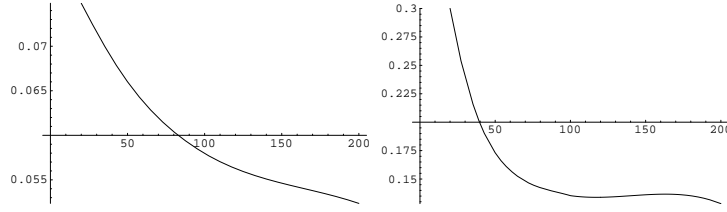


Figure 5. The parameter κ as a function of the LSP mass in the case of the $A = 127$ system, for $Q_{min} = 0$ expected in a plane perpendicular to the sun's velocity on the left and opposite to the sun's velocity on the right.

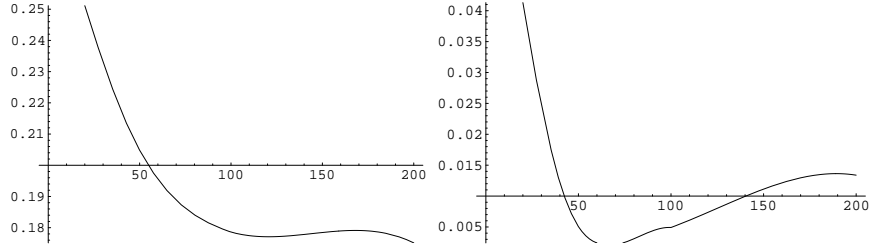


Figure 6. The modulation amplitude h_m in a plane perpendicular to the sun's velocity on the left and opposite to the sun's velocity on the right. Otherwise the notation is the same as in Fig 5.

3.4. Transitions to excited states

Incorporating the relevant kinematics and integrating the differential event rate dR/du from u_{min} to u_{max} we obtain the total rate as follows:

$$R_{exc} = \int_{u_{exc}}^{u_{max}} \frac{dR_{exc}}{du} \left(1 - \frac{u_{exc}^2}{u^2}\right) du, \quad R_{gs} = \int_{u_{min}}^{u_{max}} \frac{dR_{gs}}{du} du \quad (12)$$

where $u_{exc} = \frac{\mu_r E_x}{A m_N Q_0}$ and E_x is the excitation energy of the final nucleus, $u_{max} = (y/a)^2 - (E_x/Q_0)$, $y = v/\epsilon_0$ and $u_{min} = Q_{min}/Q_0$, Q_{min} (imposed by the detector energy cutoff) and $u_{max} = (y_{esc}/a)^2$ is imposed by the escape velocity ($y_{esc} = 2.84$).

For our purposes it is adequate to estimate the ratio of the rate to the excited state divided by that to the ground state (branching ratio) as a

function of the LSP mass. This can be cast in the form:

$$BRR = \frac{S_{exc}(0)}{S_{gs}(0)} \frac{\Psi_{exc}(u_{exc}, u_{max})[1 + h_{exc}(u_{exc}, u_{max}) \cos \alpha]}{\Psi_{gs}(u_{min})[1 + h(u_{min}) \cos \alpha]} \quad (13)$$

in an obvious notation ¹⁷). $S_{gs}(0)$ and $S_{exc}(0)$ are the static spin matrix elements. As we have seen their ratio is essentially independent of supersymmetry, if the isoscalar contribution is neglected. For ¹²⁷I it was found ⁹ to be about 2. The functions Ψ are given as follows :

$$\Psi_{gs}(u_{min}) = \int_{u_{min}}^{(y/a)^2} \frac{S_{gs}(u)}{S_{gs}(0)} F_{11}^{gs}(u) [\psi(a\sqrt{u}) - \psi(y_{esc})] du \quad (14)$$

$$\Psi_{exc}(u_{exc}, u_{max}) = \int_{u_{exc}}^{u_{max}} \frac{S_{exc}(u)}{S_{exc}(0)} F_{11}^{exc}(u) (1 - \frac{u_{exc}^2}{u^2}) [\psi(a\sqrt{u}(1 + u_{exc}/u)) - \psi(y_{esc})] du \quad (15)$$

The functions ψ arise from the convolution with LSP velocity distribution. The obtained results are shown in Fig. 7.

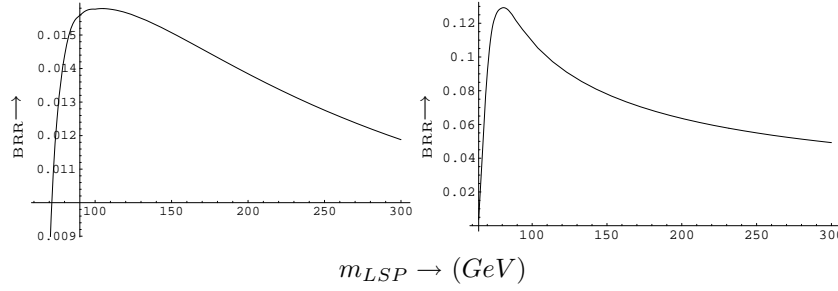


Figure 7. The ratio of the rate to the excited state divided by that of the ground state as a function of the LSP mass (in GeV) for ¹²⁷I. We assumed that the static spin matrix element of the transition from the ground to the excited state is a factor of 1.9 larger than that involving the ground state, but the functions $F_{11}(u)$ are the same. On the left we show the results for $Q_{min} = 0$ and on the right for $Q_{min} = 10$ KeV.

4. Conclusions

Since the expected event rates for direct neutralino detection are very low^{5,8}, in the present work we looked for characteristic experimental signatures for background reduction, such as:

Standard recoil experiments. Here the relevant parameters are t and h .

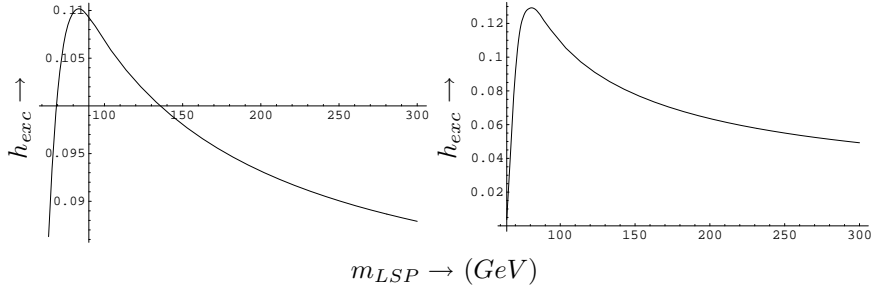


Figure 8. The the same as in Fig. 3 for the modulation amplitude h_{exc} for the transition to the excited state.

For light targets they are essentially independent of the LSP mass¹⁷, essentially the same for both the coherent and the spin modes. The modulation is small, $h \approx 0.2\%$, but it may increase as Q_{min} increases. Unfortunately, for heavy targets even the sign of h is uncertain for $Q_{min} = 0$. The situation improves as Q_{min} increases, but at the expense of the number of counts.

Directional experiments¹⁶. Here we find a correlation of the rates with the velocity of the sun as well as that of the Earth. One encounters reduction factors $\kappa/2\pi$, which depend on the angle of observation. The most favorable factor is small, $\approx 1/4\pi$ and occurs when the nucleus is recoiling opposite to the direction of motion of the sun. As a bonus one gets modulation, which is three times larger, $h_m \approx 0.06$. In a plane perpendicular to the sun's direction of motion the reduction factor is close to $1/12\pi$, but now the modulation can be quite high, $h_m \approx 0.3$, and exhibits very interesting time dependent pattern (see Table 2. Further interesting features may appear in the case of non standard velocity distributions¹⁵.

Transitions to Excited states. We find that branching ratios for transitions to the first excited state of ^{127}I is relatively high, about 10%. The modulation in this case is much larger $h_{exc} \approx 0.6$. We hope that such a branching ratio will encourage future experiments to search for characteristic γ rays rather than recoils. Acknowledgments: This work was supported in part by the European Union under the contracts RTN No HPRN-CT-2000-00148 and MRTN-CT-2004-503369. Part of this work was performed in LANL. The author is indebted to Dr Dan Strottman for his support and hospitality.

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